The Latest PHENIX Results on Forward and Central Flow

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Outline

- Analyses recently submitted for publication
  - v_2 and v_4 of unidentified hadrons [arXiv:1003.5586]
  - v_2 of heavy flavor quarks [arXiv:1005.1627]
- Ongoing Analyses
  - v_2 of ^2H, Λ and ϕ
  - v_2 of unidentified hadrons at forward angles

Hot Off the Presses

All data shown used

- 200 GeV Au+Au
- Some variation of **Reaction Plane Method** to extract flow signal

v_2, v_4 of Unidentified Charged Hadrons [arXiv:1003.5586]

Importance

- v_4 argued to be more sensitive than v_2 in constraining shear_viscosity/entropy (η/s) value
- Also sensitive to freeze-out dynamics
- $v_4/(v_2)^2$ ratio can indicate if full local equilibrium is reached (pure hydro ratio ~ 0.5)

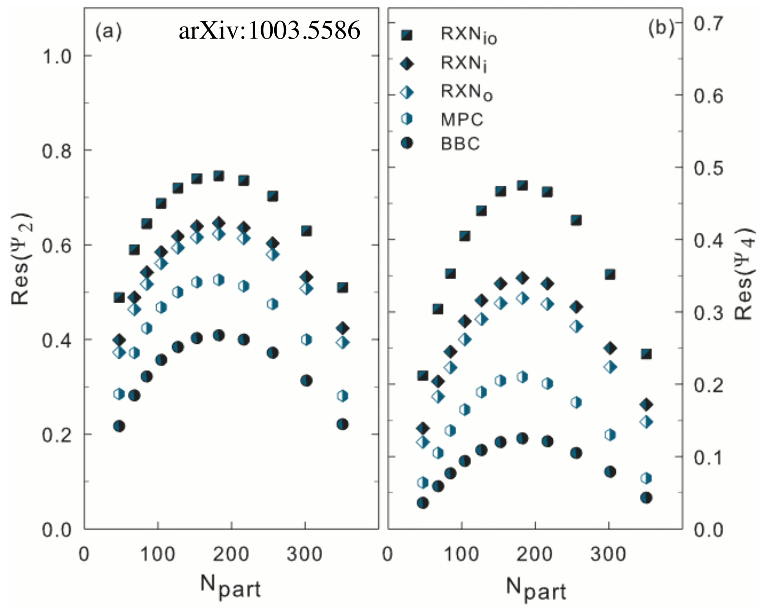
v_2, v_4 $h^{\pm}$ Analysis Footnotes

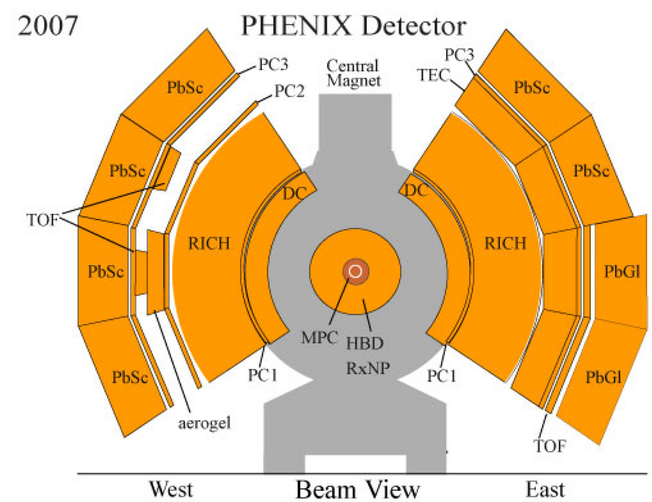
- Run-7, ~3.6 billion evts
- Large dataset allows precise measurements at low p_T

Reaction Plane Detectors

BBC	$3.1<\lvert\eta\rvert<3.9$
MPC	$3.1<\lvert\eta\rvert<3.7$
RXNP_out	$1.0<\lvert\eta\rvert<1.5$
RXNP_in	$1.5<\lvert\eta\rvert<2.8$
RXNP_full	$1.0<\lvert\eta\rvert<2.8$

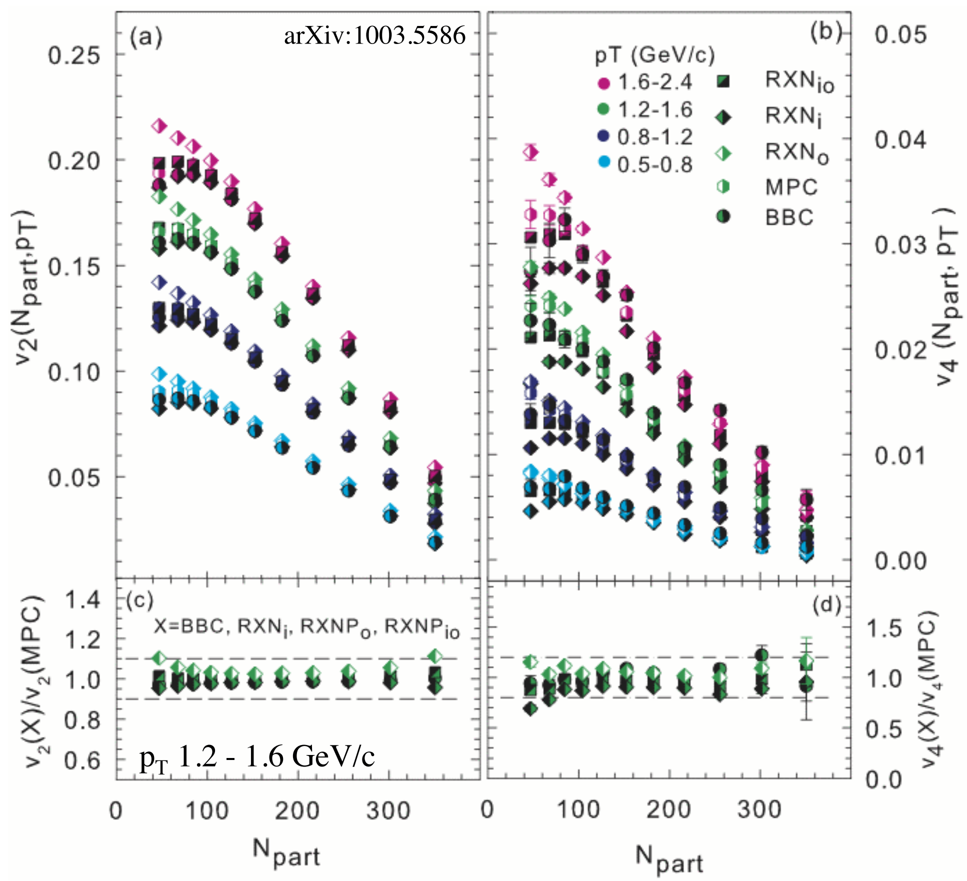
- Used 2nd harmonic event plane for both v_2 and v_4
- Tracks identified using DC, PC & EMCal





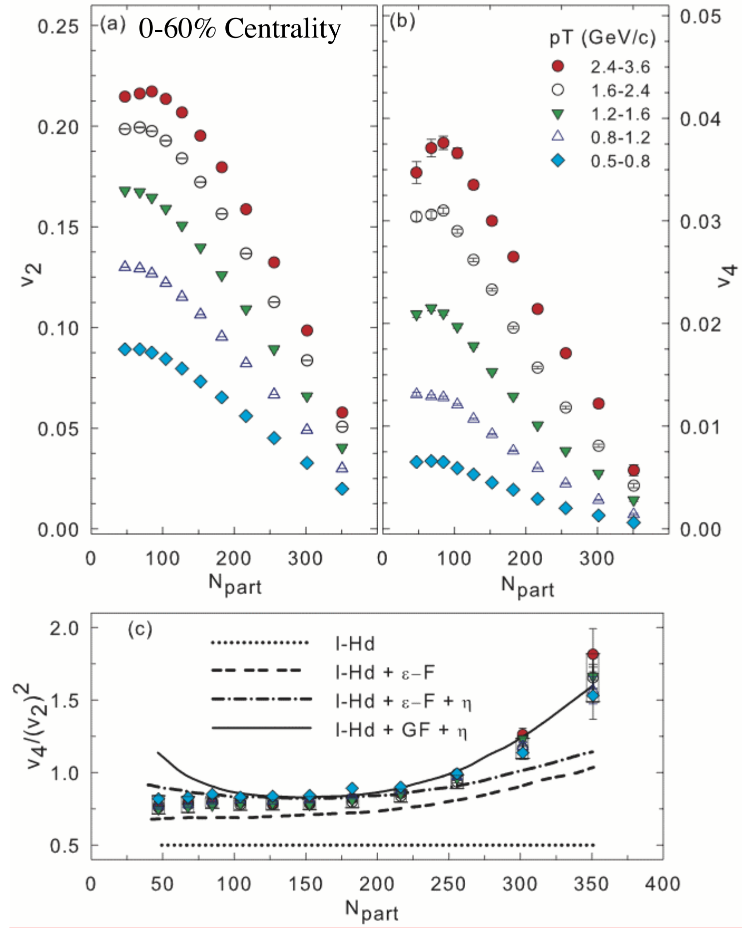
v_2, v_4 $h^{\pm}$ Results

- RP detectors with different η ranges yield similar signal
- Signal varies v_2 (v_4)
  - mid-central ~5% (10%)
  - central/peripheral 10% (20%)
- Signals agree within systematic errors (v_2 = 10%, v_4 = 20%)
- **Indicates reliable measurement largely free of η and p_T dependent non-flow effects within the measured range (p_T = 0.5 - 2.4 GeV/c)**



v_2, v_4 $h^{\pm}$ Results

- Fig (a) & (b)
  - v_2 and v_4 signal have similar shape
- Fig (c) - $v_4/(v_2)^2$
  - Ratio independent of p_T within 0.5-3.6 GeV/c
  - $v_4/(v_2)^2 \approx 0.8$ for $\sim 50 < N_{part} < 200$, which is greater than ideal hydro (dot-dot)
  - adding eccentricity fluctuations within hydro model fits data better (dash-dash)
  - Even better fit when η added to hadron gas phase and small η added to QGP phase (dot-dash)
  - Ratio significantly increases $N_{part} > \sim 200$
  - Additional fluctuations needed to match central data (solid)
  - **Fit with data implies a small η/s**



Data gives strong indication of hydrodynamic behavior in matter created at RHIC

These precision measurements should provide stringent constraints for models.

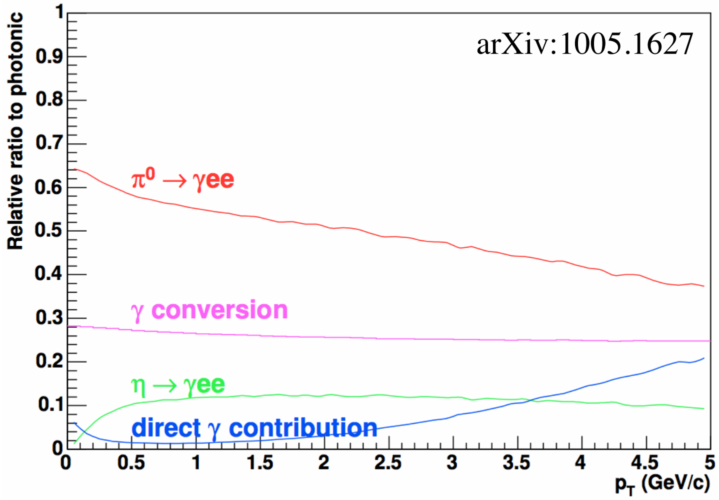
v_2 of Heavy Flavor (HF) Quarks [arXiv:1005.1627]

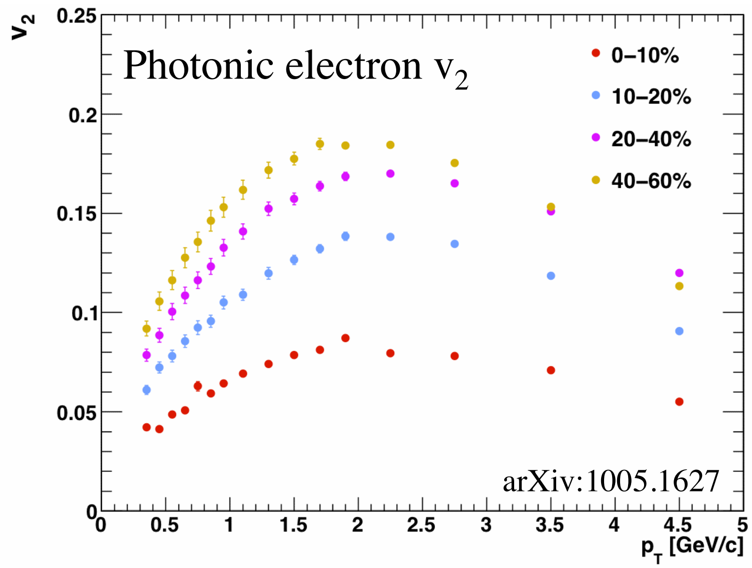
Importance

- Heavy quarks are good probes for the medium because they are created early in collision by hard scattering
- Because of their large mass they may interact differently with the medium than lighter quarks.
- Matter is strongly interacting, but is it strong enough for heavy quarks to flow? And if so, how large is the flow?

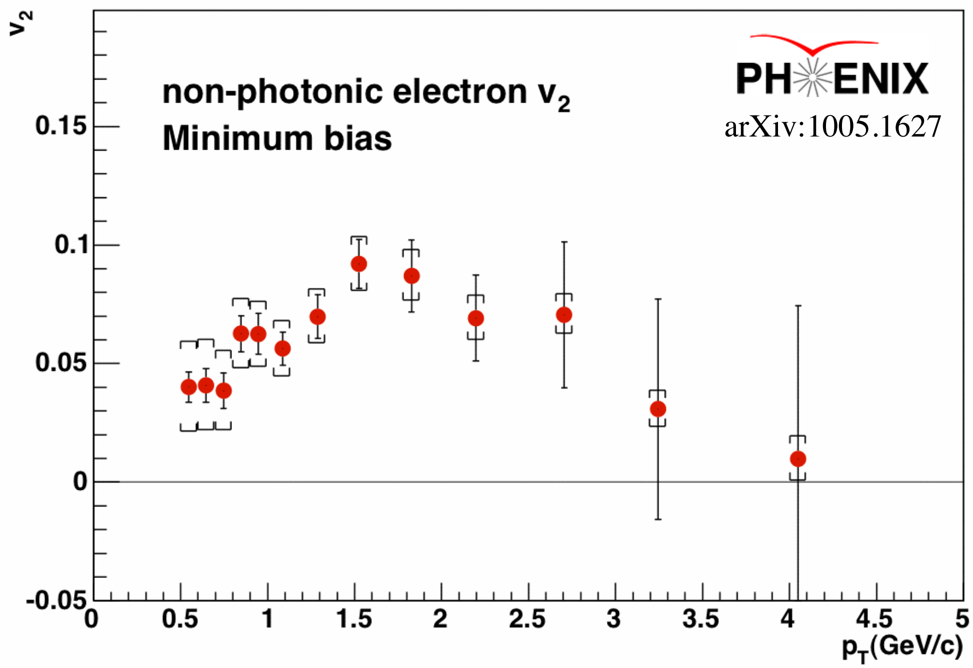
HF v_2 Analysis Footnotes

- Run-4, ~700M evts
- Measured heavy flavor using single electrons from semileptonic decays (~10% branching ratio)
- Tracking done using DC, PC, RICH and EMCal
- RICH is primary electron identifier
- Photonic electron bkgrd subtracted using "cocktail method" where background v_2 was estimated using a Monte Carlo simulation with input from measured data
- Photonic cocktail included electrons from π^0 and η decays and γ conversions and direct γ
- Electron v_2 from K decays was also subtracted





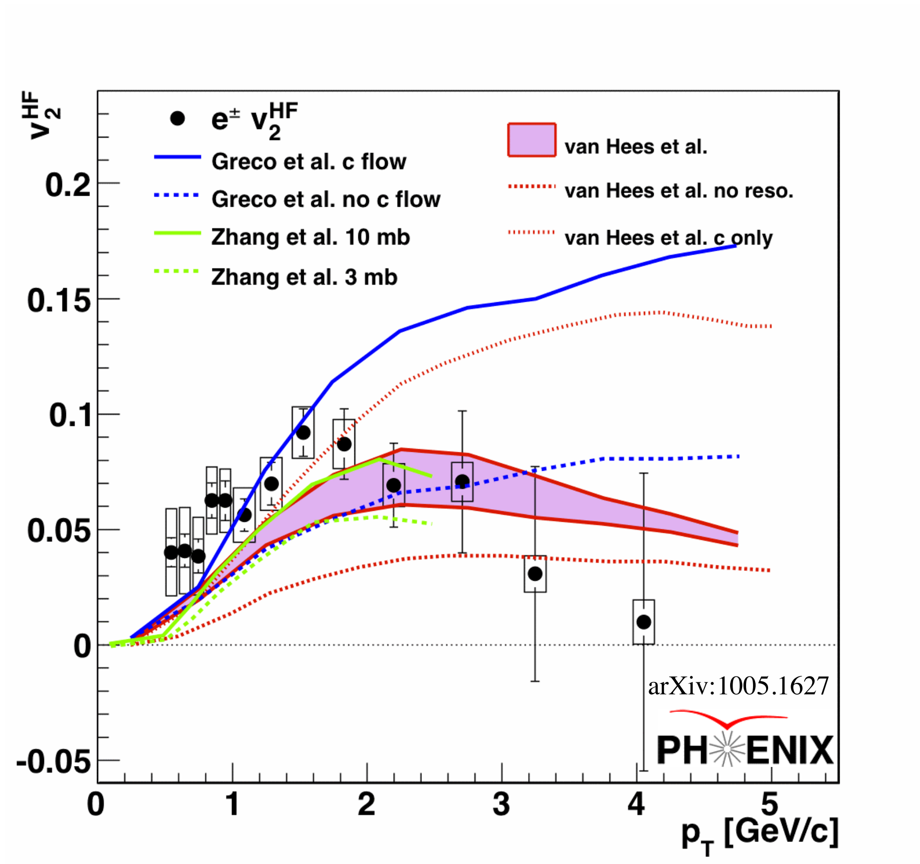
HF v_2 Results



- Positive v_2 at low p_T - indicates heavy quarks (mainly charm) couple with the medium.
- Shape similar to lighter quarks except at highest p_T.
- Although errors are large at high p_T the signal appears to fall significantly from peak. This indicates a change in energy loss mechanism or a growing contribution from the bottom quark.

Model Comparisons

- All models include quark coalescence
- Models that best describe low p_T data are:
  - Greco et al. with charm flow
  - Zhang et al. with larger charm quark parton-scattering cross section (σ = 10 mb)
  - van Hees et al. with resonance interactions
- Indicates
  - heavy quarks participate in the medium
  - Coalescence and resonance are large contributors to HF v_2 at low p_T



Ongoing Analyses

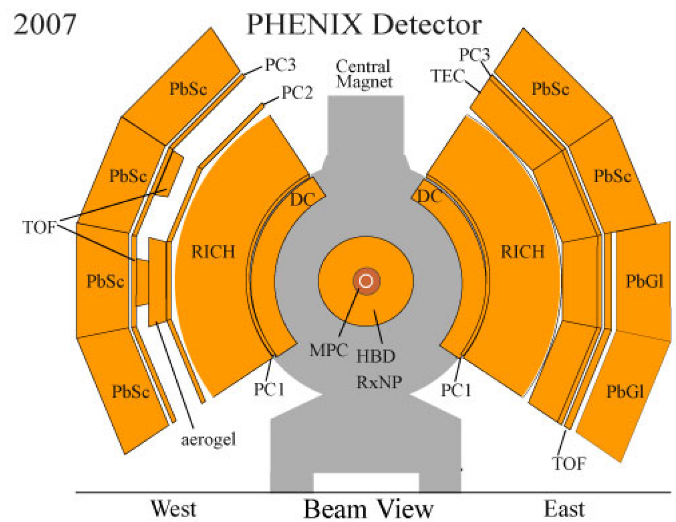
v_2 of ^2H, Λ and ϕ

Importance

- Does constituent quark scaling continue to higher p_T with heavier hadrons?
- Multi-strange hadrons (ϕ) are expected to have a small hadron cross section rendering them less sensitive to the later hadronic stage of the collision.
- Therefore, the primary origin of their flow would develop at the partonic level, making them a good probe for the QGP.

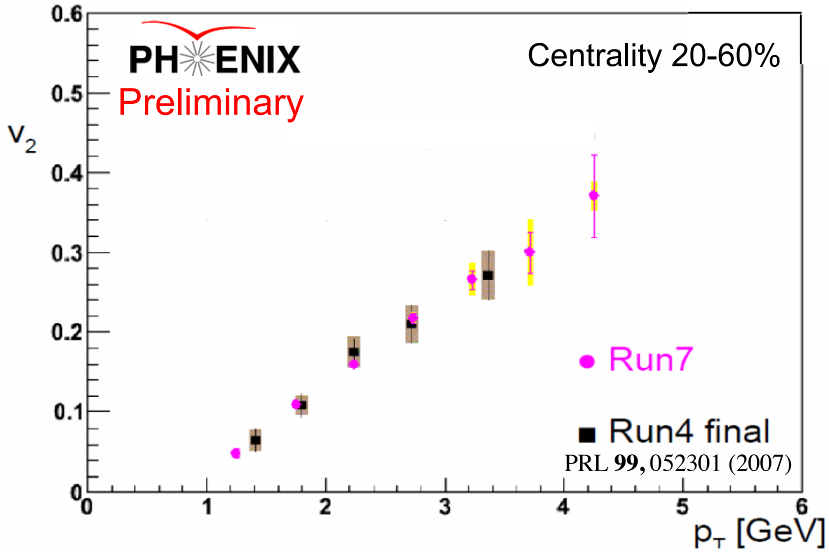
^{2}H, Λ and φ Analysis Footnotes

- Run-7
- Improved RP resolution with RXNP over BBC used in Run-4
- Identified particles using EMCal, TOF. E. and TOF. W.

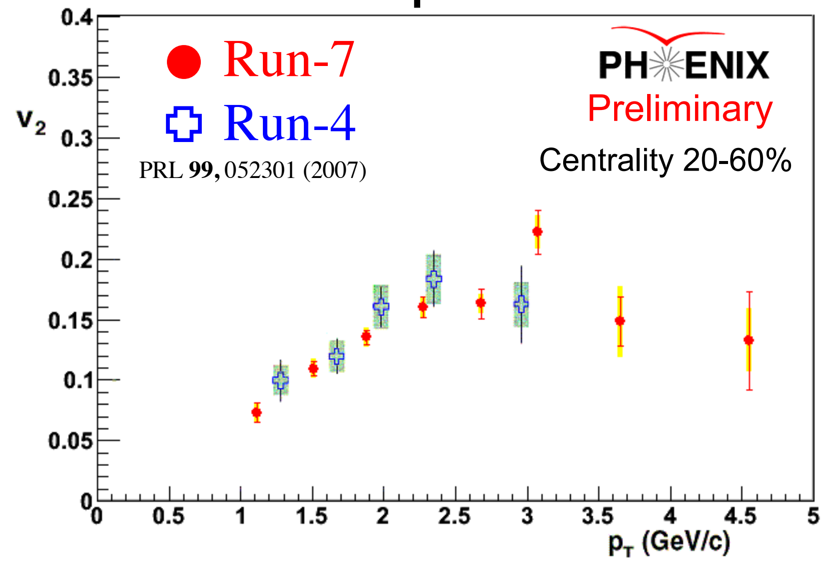


^2H and ϕ v_2 Results

^2H



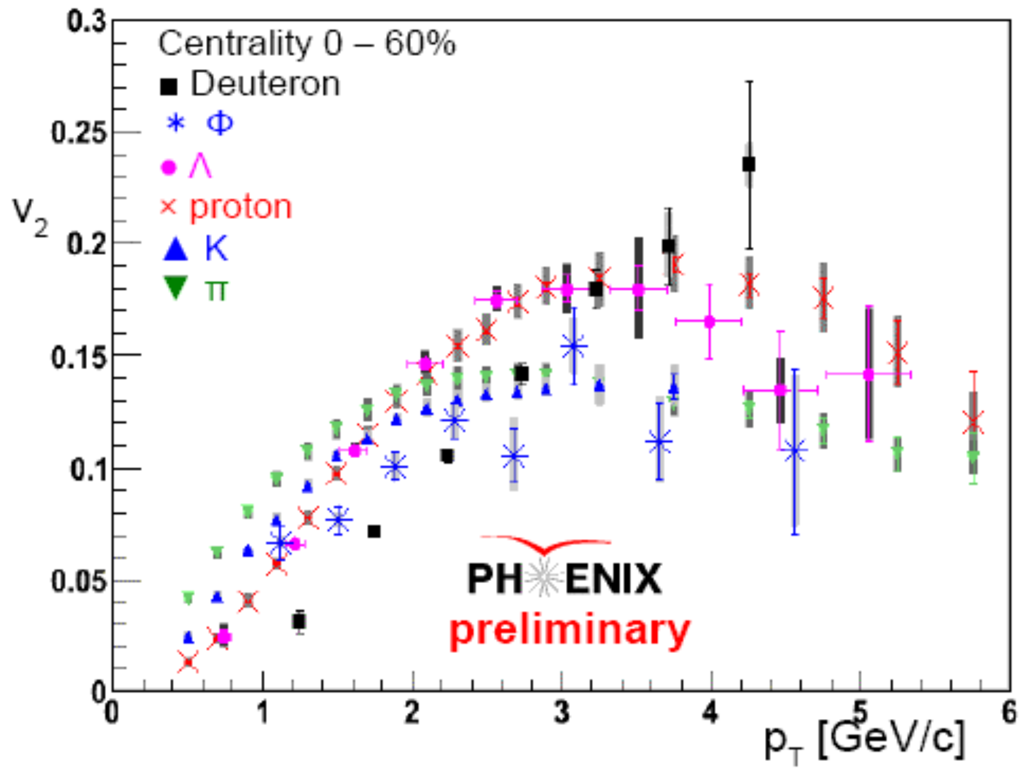
ϕ



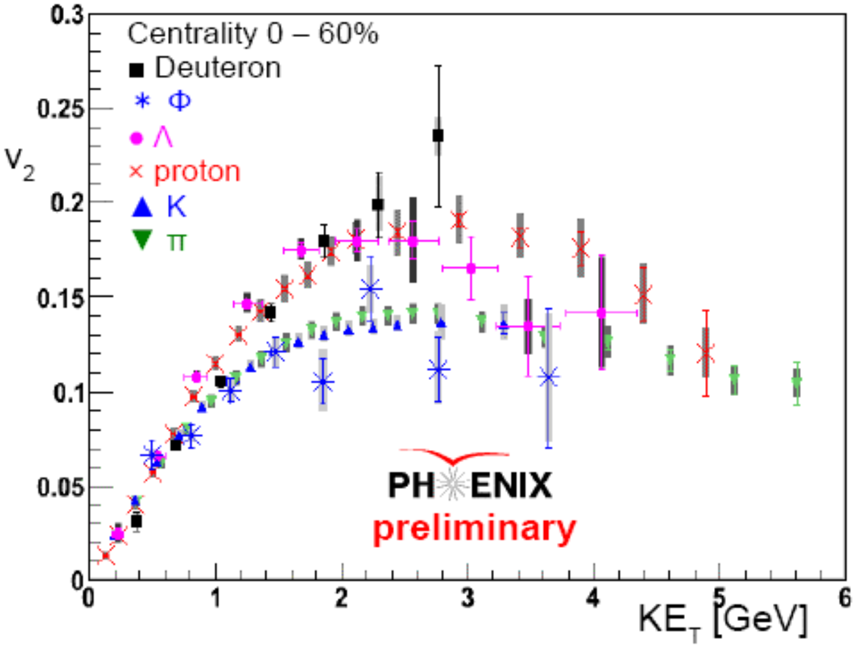
- Run-7 and Run-4 measurements are consistent
- Run-7 has improved statistics and RP resolution allowing for higher p_T measurement

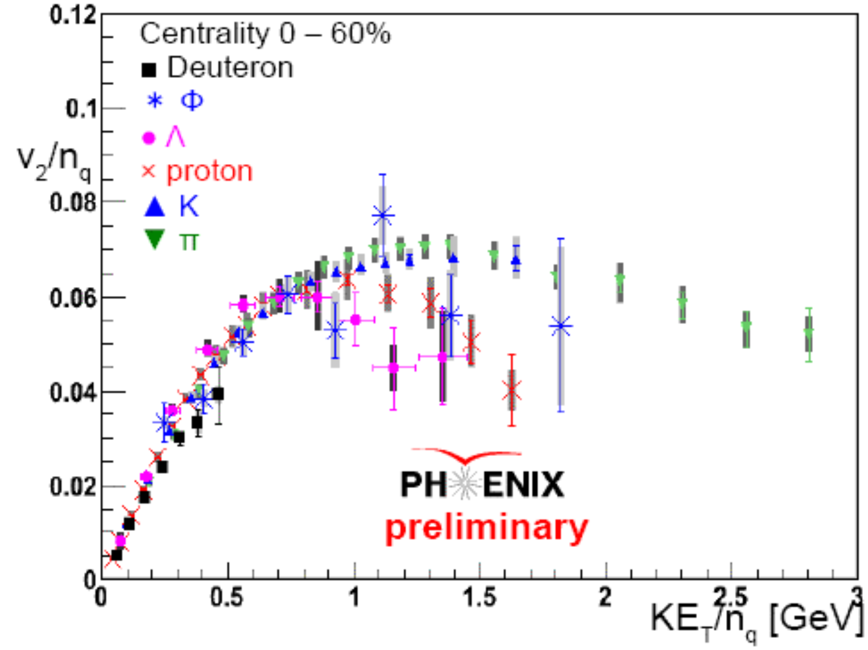
^{2}H, Λ and ϕ v_2 Results

- Mass ordering is followed at $p_T < 2$ GeV/c
- At p_T 2 - 5 GeV/c ϕ follows other mesons (π, K) despite having a mass closer to proton and Λ baryons
- ϕ exhibits strong flow signal indicating flow develops at partonic level because of its small hadronic cross section
- Λ signal similar to proton
  - similar mass
  - same quark number
- ^{2}H signal becomes larger than proton at $p_T \approx 3$ GeV/c and is expected to rise further



KE_T Scaling



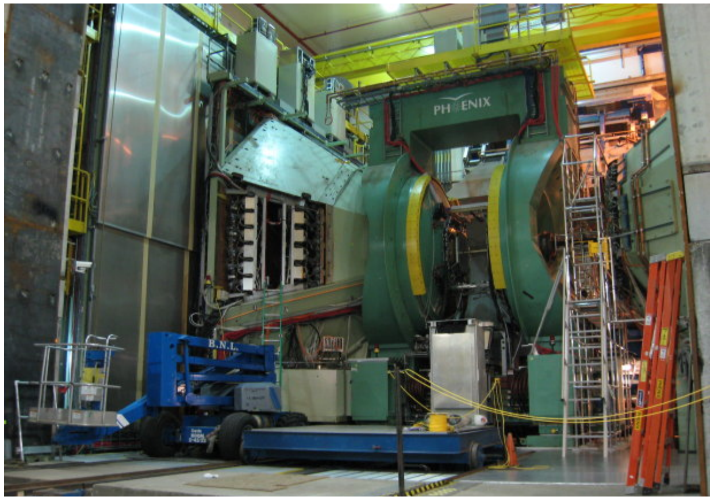


- Meson and Baryon transverse kinetic energy (KE_T) scaling diverges between ~1 - 4 GeV
- KE_T/n_q scaling consistent for all particles below ~1 GeV
- Deviation at higher values indicates change in v_2 and/or particle production mechanism

v_2 of Unidentified Hadrons at Forward Angles

Importance

- Measured using PHENIX's forward angle spectrometers (Muon Arms).
- The muon arms are unique because they have an η coverage of |1.2| < η < |2.2| and are the only detectors at RHIC capable of measuring $v_2(p_T)$ over the entirety of this η region.
- This measurement will help to better understand how v_2 changes with η.



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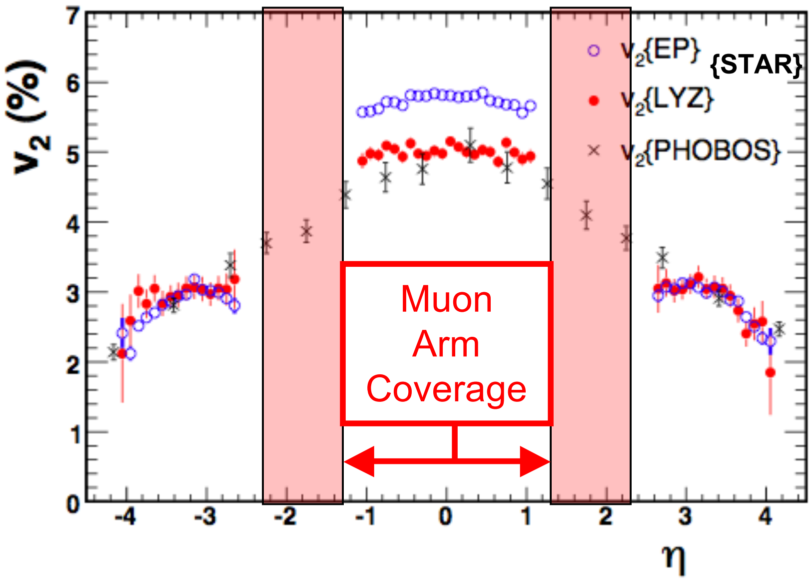
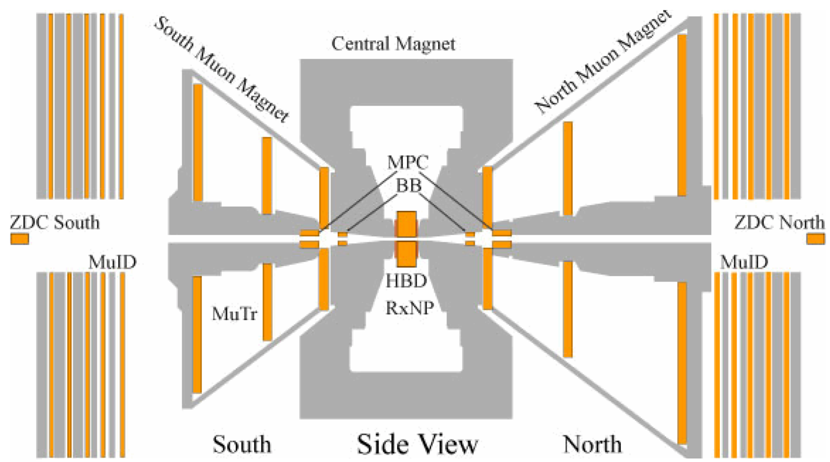
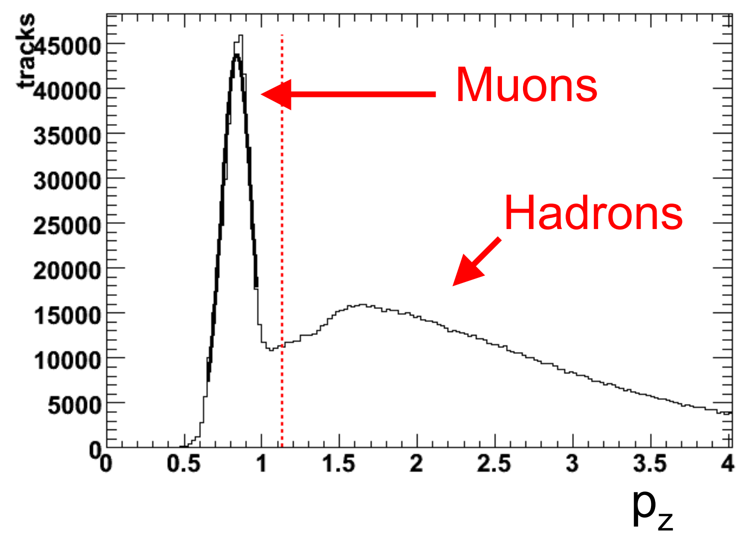


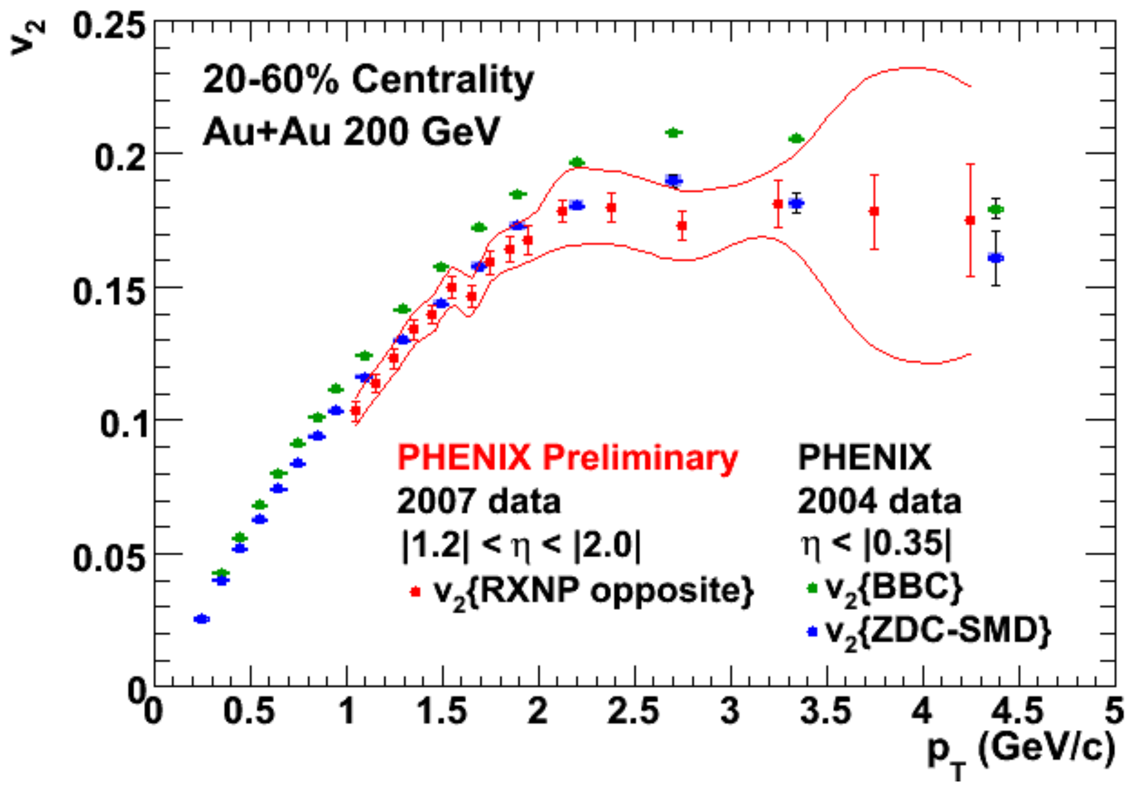
Forward η v_2 Analysis Footnotes

- Run-7
- Estimated Ψ using opposite arm RXNP from muon arm
- Used MuTr and MuID for tracking
- Identified hadrons from muons by applying a momentum cut to tracks that stop in the MuID





Comparison to mid-rapidity

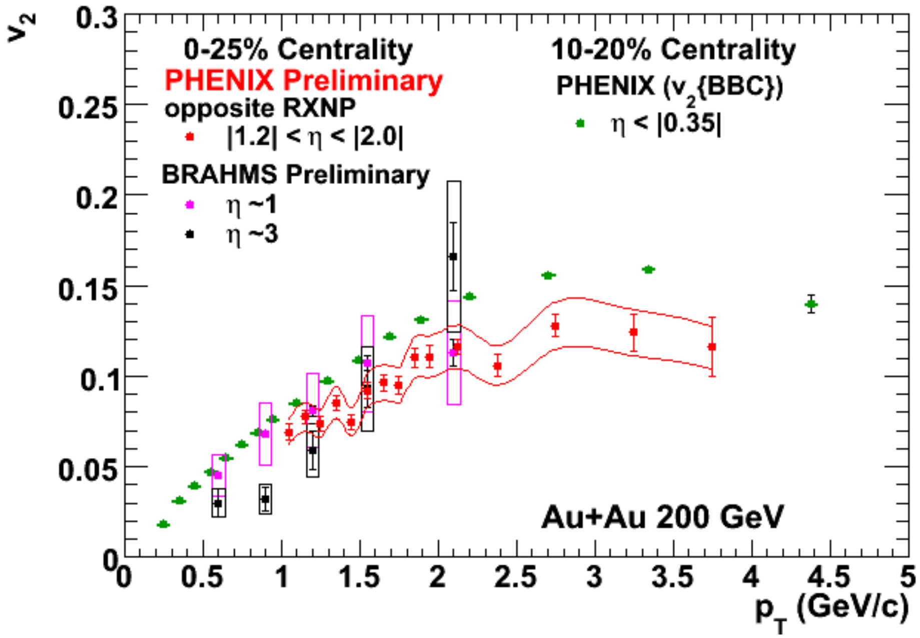


Different η regions yield similar results.

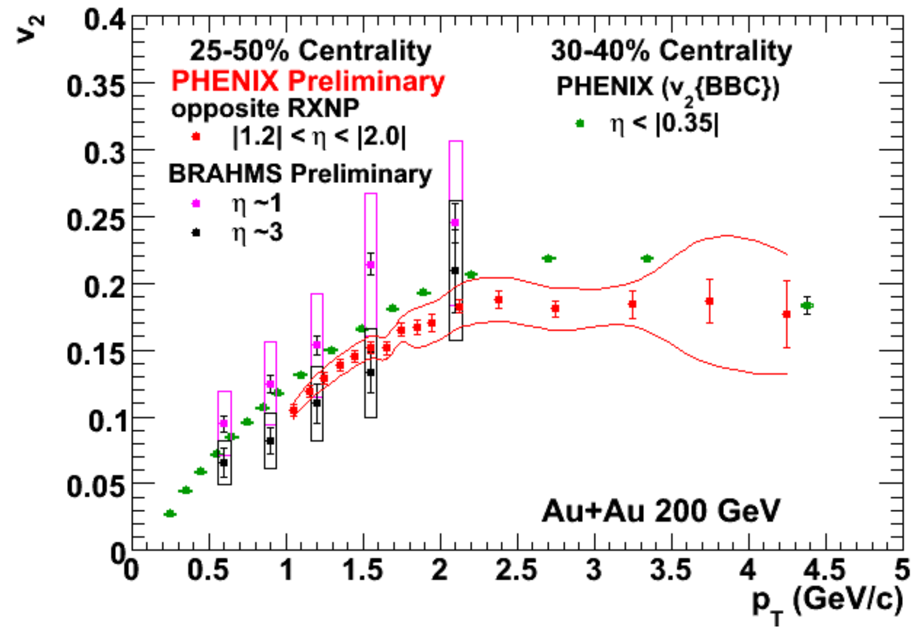
Comparing different η

- Plotting $v_2(p_T)$ at 4 different η ranges from 0->3.

Compare:
0-25% Forward vs 10-20% Mid



Compare:
25-50% Forward vs 30-40% Mid



- Data points indicate a falling signal with increasing η, but this is not certain when including errors.

Submission for Publication <u>Imminent</u>

v_2 of High p_T π^0's

Important for understanding path length dependence of jet energy loss

Stay tuned!!!

Conclusion

- PHENIX has a variety of exciting new flow measurements
- With the help of theorists these measurements should bring new insights into RHIC collisions and the properties of the QGP
- New insights will continue with the newly collected 200 GeV and low energy Run-10 data sets and PHENIX's ongoing detector upgrades programs such as VTX & FVTX

Backup

HF v_2 background

$$v_{2_e}^{non-\gamma} = \frac{(1+R_{NP})v_{2_e} - v_{2_e}^{\gamma}}{R_{NP}}$$

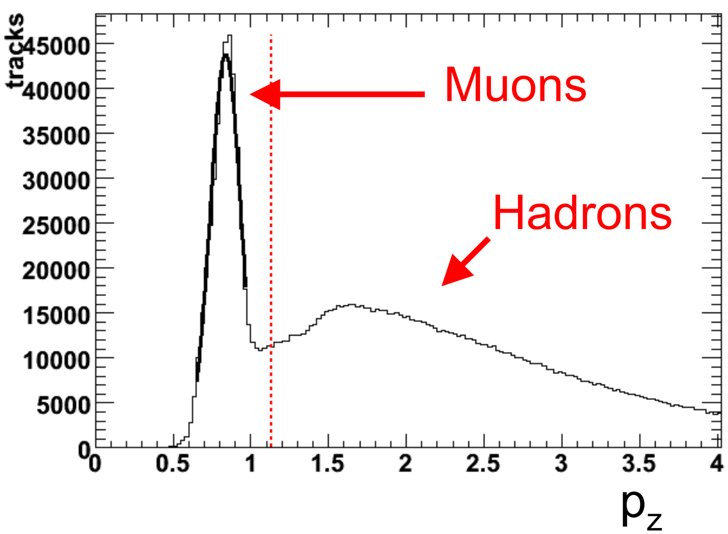
$v_{2e}{}^{\text{non-}\gamma}$ = non-photonic electron
$v_{2e}{}^{\gamma}$ = photonic electron
v_{2e} = inclusive electron
R_{NP} = ratio of non-photonic/photonic yields

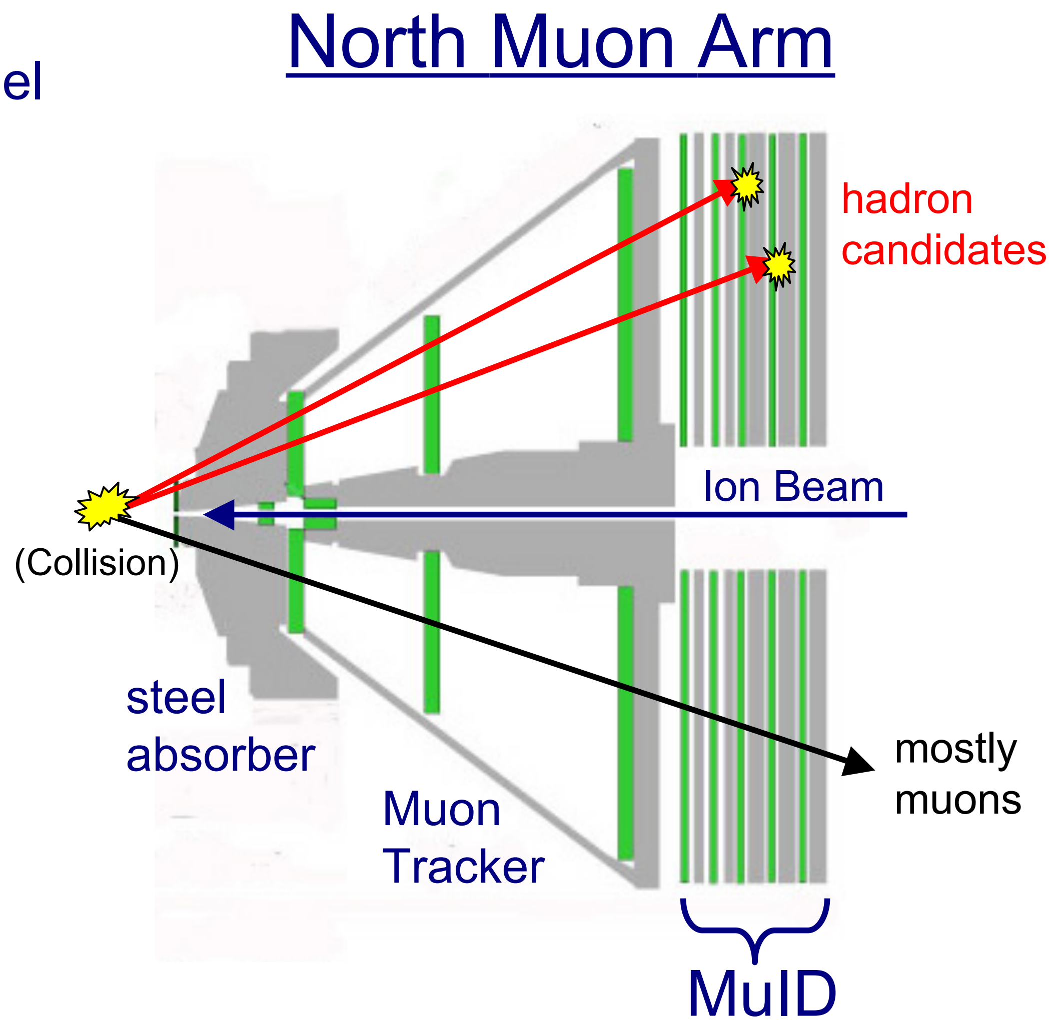
$$v_{2_e}^{heavy} = \frac{v_{2_e}^{non-\gamma} - R_{KNP} v_{2_e}^{K}}{1 - R_{KNP}}$$

$v_{2e}{}^{heavy}$ = heavy flavor
$v_{2e}{}^{K}$ = Kaon
R_{KNP} = ratio of electron yield from kaon decays to all other non-photonic sources

Hadron Identification

- Use Muon Identifier (MuID)
  - 5 alternating layers of steel absorber and low resolution tracking chambers
- Use only tracks that stop in MuID.
- Plot p_z distribution of stopped tracks.



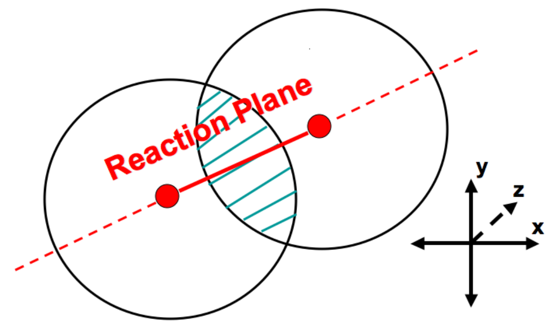


Comparison to mid-rapidity

- Due to differences in initial particle composition and the steel absorber in front of the muon arms, the particle composition used to measure v_2 at mid and forward angles isn't exactly apples to apples.
- However, a comparison is still of interest.

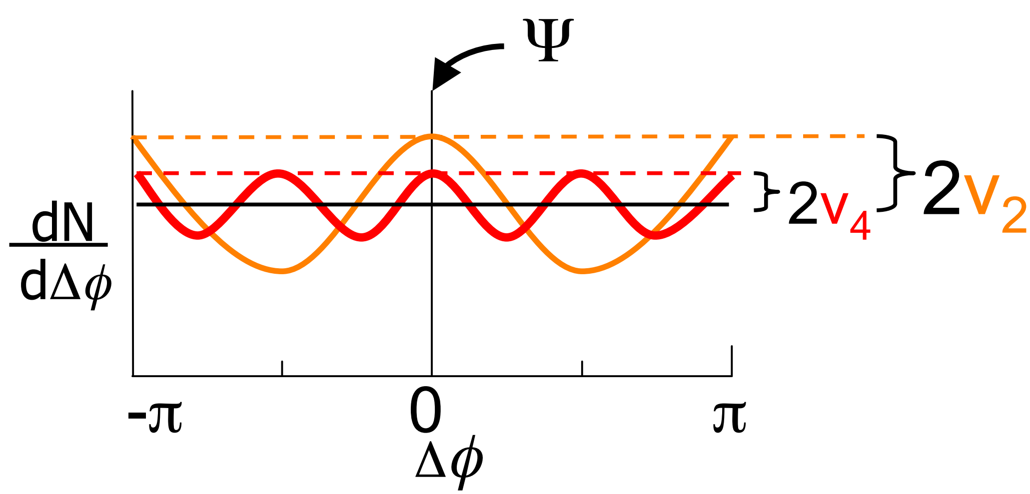
Introduction to Flow

- Flow is the asymmetric distribution of produced particles in the azimuthal direction with respect to the reaction plane angle (Ψ)
- Distribution can be described by Fourier expansion
- v_2 and v_4 are the anisotropy parameters which allow for quantifying the size of the asymmetry



$$\frac{dN}{d\Delta\phi} \propto 1 + 2v_2\cos 2(\Delta\phi) + 2v_4\cos 4(\Delta\phi) + \ldots$$

$\Delta\phi$ = angle of particle wrt Ψ



Reaction Plane Method

- All flow results shown here used some variation of the Reaction Plane Method

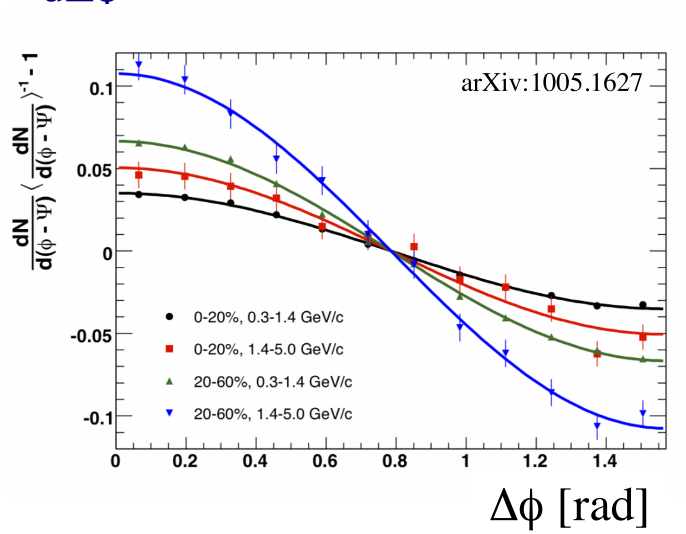
Calculation Method

$$v_n^{raw} = \langle \cos(n(\Delta\phi)) \rangle$$

n = Fourier harmonic being measured

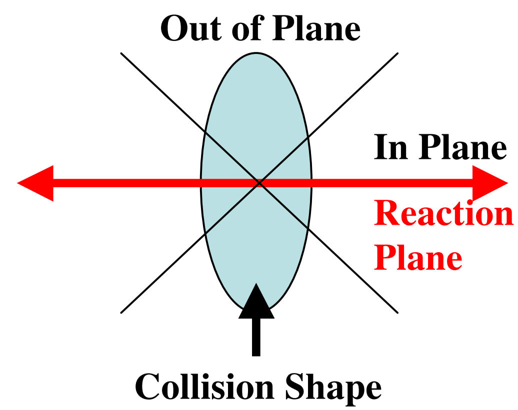
Fit Method

$$\frac{dN}{d\Delta\phi} = N_0(1+2v_n^{raw}\cos(n\Delta\phi))$$



In-Out Method

$$v_n^{raw} = \frac{\pi}{4}\frac{(N_{in} - N_{out})}{(N_{in} + N_{out})}$$



corrected flow signal $\Rightarrow$ $\boxed{v_n = \frac{v_n^{raw}}{Res}}$

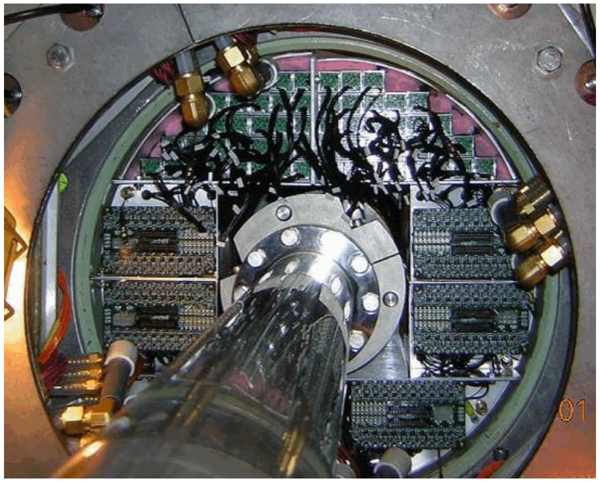
Res = resolution of reaction plane detector

PHENIX Reaction Plane Detectors

BBC

Quartz Cherenkov radiators with mesh PMT's

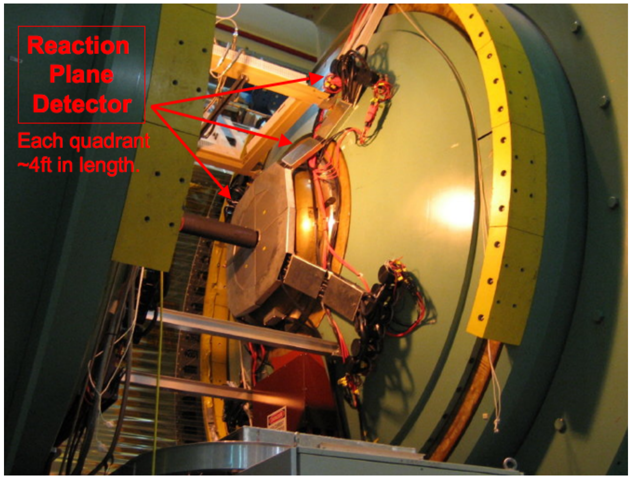
$3.1 > |\eta| < 3.9$



MPC

$PbWO_4$ Calorimeter

$3.1 > |\eta| < 3.7$



RXNP

2 concentric rings of scintillator paddles

$1.0 > |\eta_{Out}| < 1.5$
$1.5 > |\eta_{In}| < 2.8$

Reaction Plane Resolution

2 sub-event method

$$\mathrm{Re}\,s = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi \exp\left(\frac{-\chi^2}{4}\right)\left[I_{(n-1)/2}\left(\frac{\chi^2}{4}\right) + I_{(n+1)/2}\left(\frac{\chi^2}{4}\right)\right]$$

where $\chi = \sqrt{2N}$

N = number of particles

I_x = modified Bessel functions

3 sub-event method

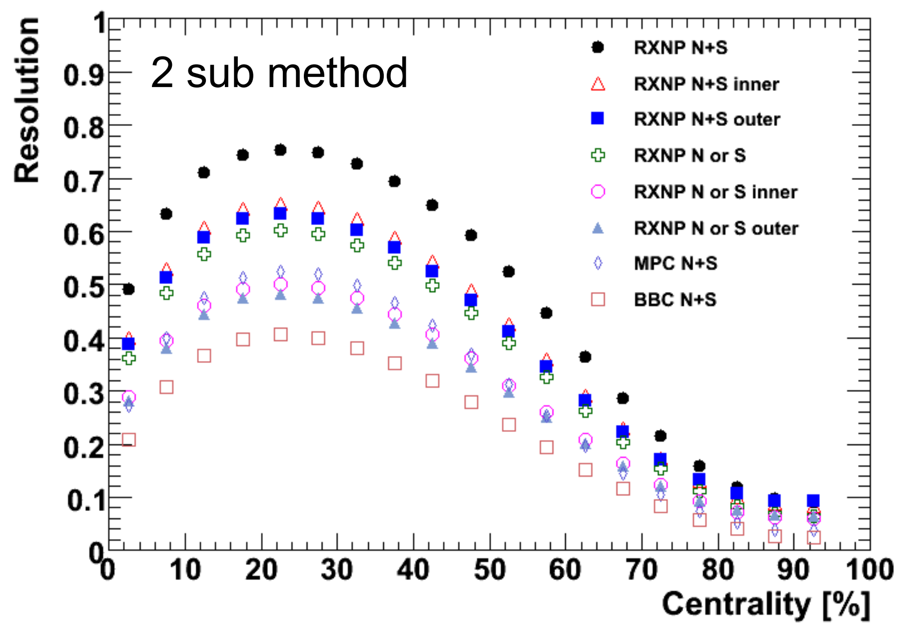
$$\mathrm{Re}\,s(\Psi^a) = \sqrt{\frac{\langle\cos(n(\Psi^a - \Psi^b))\rangle\langle\cos(n(\Psi^a - \Psi^c))\rangle}{\langle\cos(n(\Psi^b - \Psi^c))\rangle}}$$

Finds Ψ^a Res using Ψ^b and Ψ^c

2 sub-event estimation

$$\mathrm{Re}\,s(\Psi^{ab}) = \sqrt{2(\cos(n(\Psi^a - \Psi^b))}$$

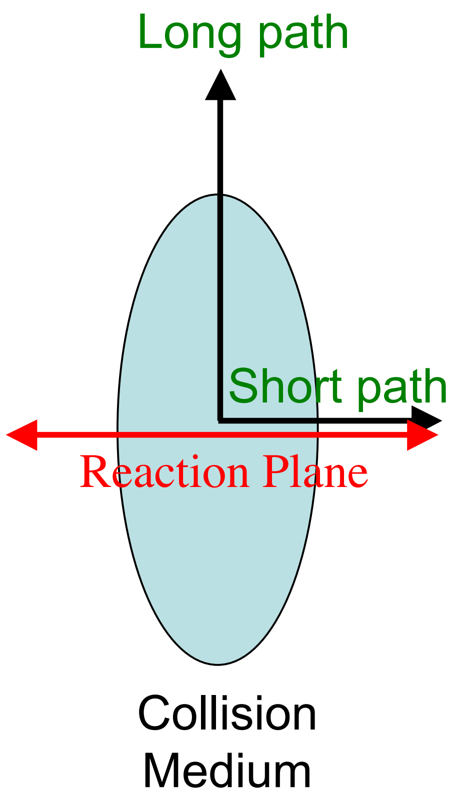
Only used for BBC where Res is poor



High p_T π^0 v_2 Importance

- v_2 is sensitive to path length dependence of energy loss
- v_2 of high p_T particles can lead to a better understanding of jet energy loss and jet suppression
- How strongly coupled is the jet to the medium?

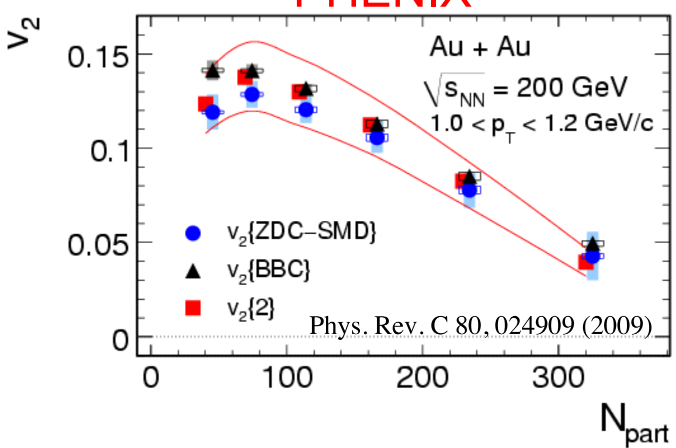
- Stay tuned!!!



v_2 Highlights at RHIC

- $h^{\pm}$ v_2 has been measured by all 4 RHIC experiments
- Each measuring a strong signal indicating medium is dense, strongly interacting and thermalizes quickly before expansion.

PHENIX



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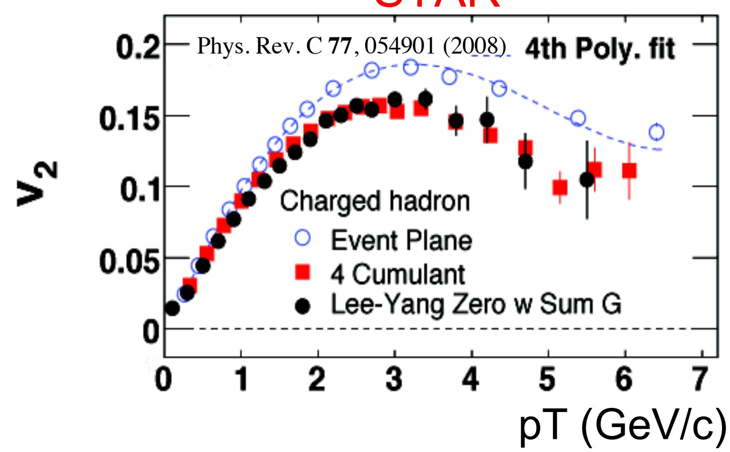

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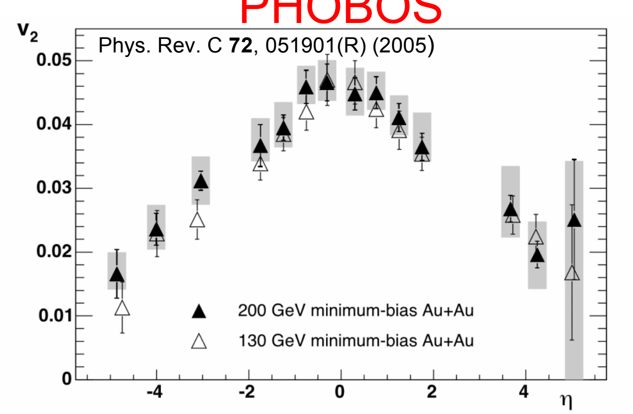
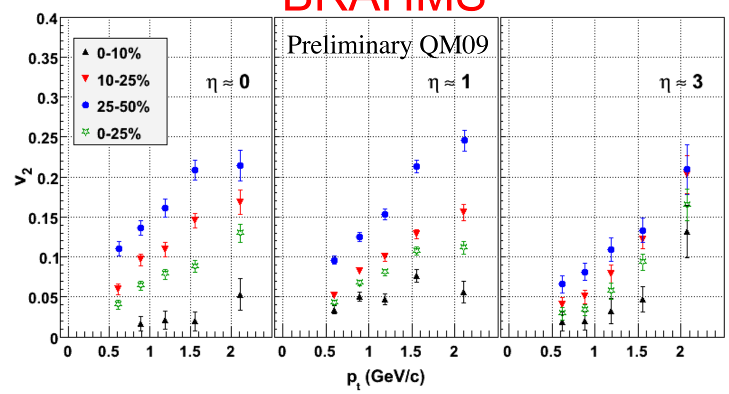


BRAHMS



v_2 Highlights at RHIC

- $h^{\pm}$ v_2 has been measured by all 4 RHIC experiments
- Each measuring a strong signal indicating medium is dense, strongly interacting and thermalizes quickly before expansion.
- Low p_T data is described well by hydrodynamic models indicating the medium behaves like a liquid.

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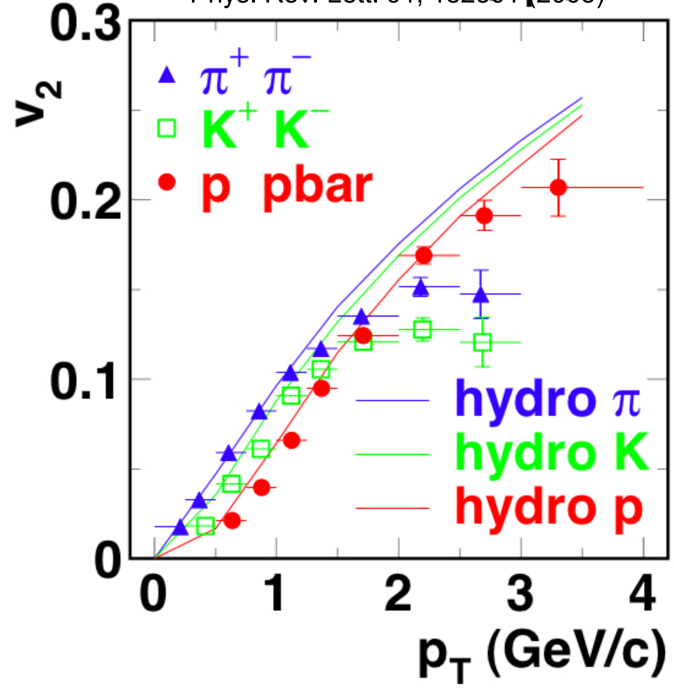

v_2 KE_T/n_q scaling

- Different particles exhibit KE_T/n_q scaling suggesting flow develops at the quark level, which provides strong evidence for QGP formation